Exotic Higgs Decays

Rouven Essig

Yang Institute for Theoretical Physics, Stony Brook

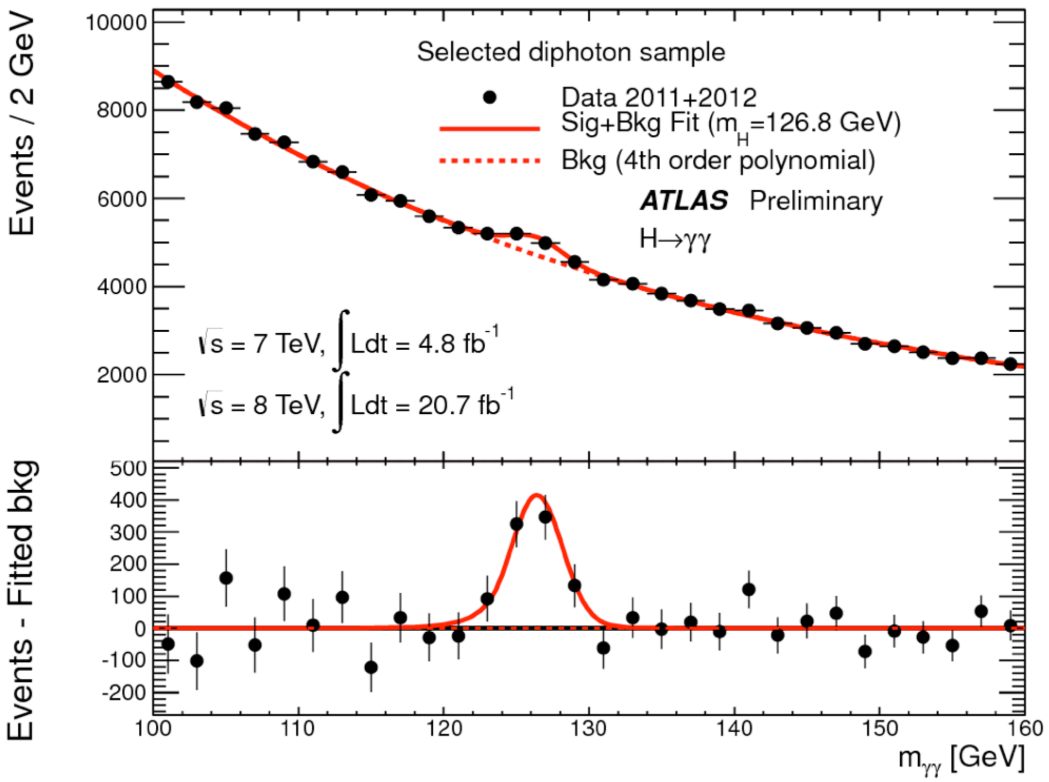
for the “Exotic Higgs Decay Working Group”

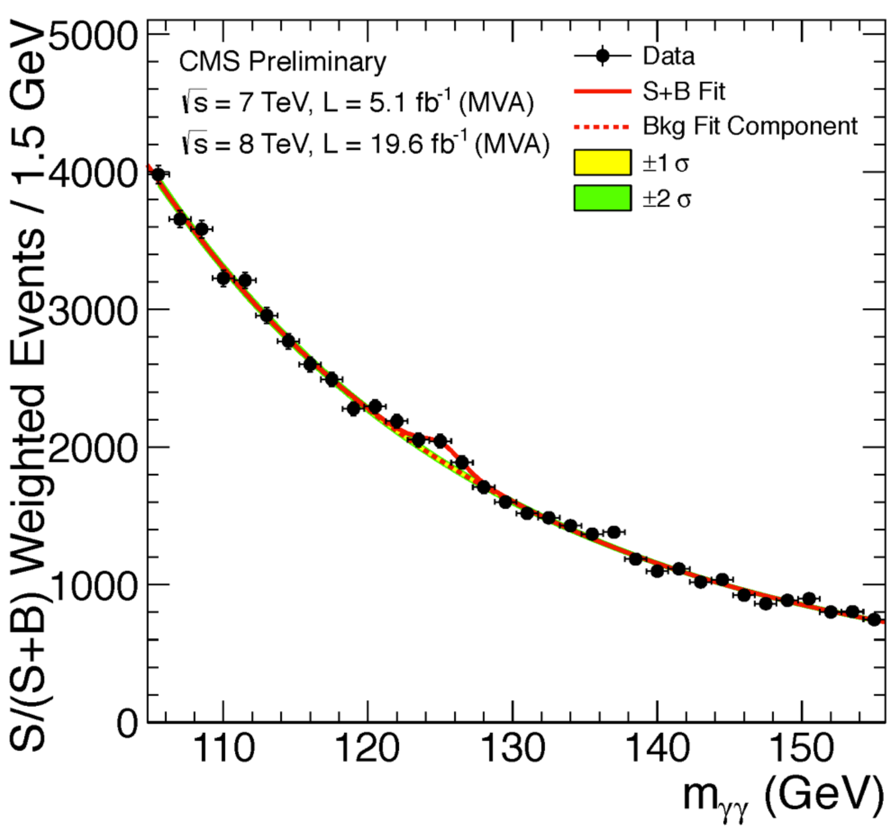
D. Curtin, RE, S. Gori, P. Jaiswal, A. Katz, T. Liu,
D. McKeen, J. Shelton, Z. Surujon, B. Tweedie, Y. Zhong

Snowmass Energy Frontier Workshop @BNL

4/4/2013

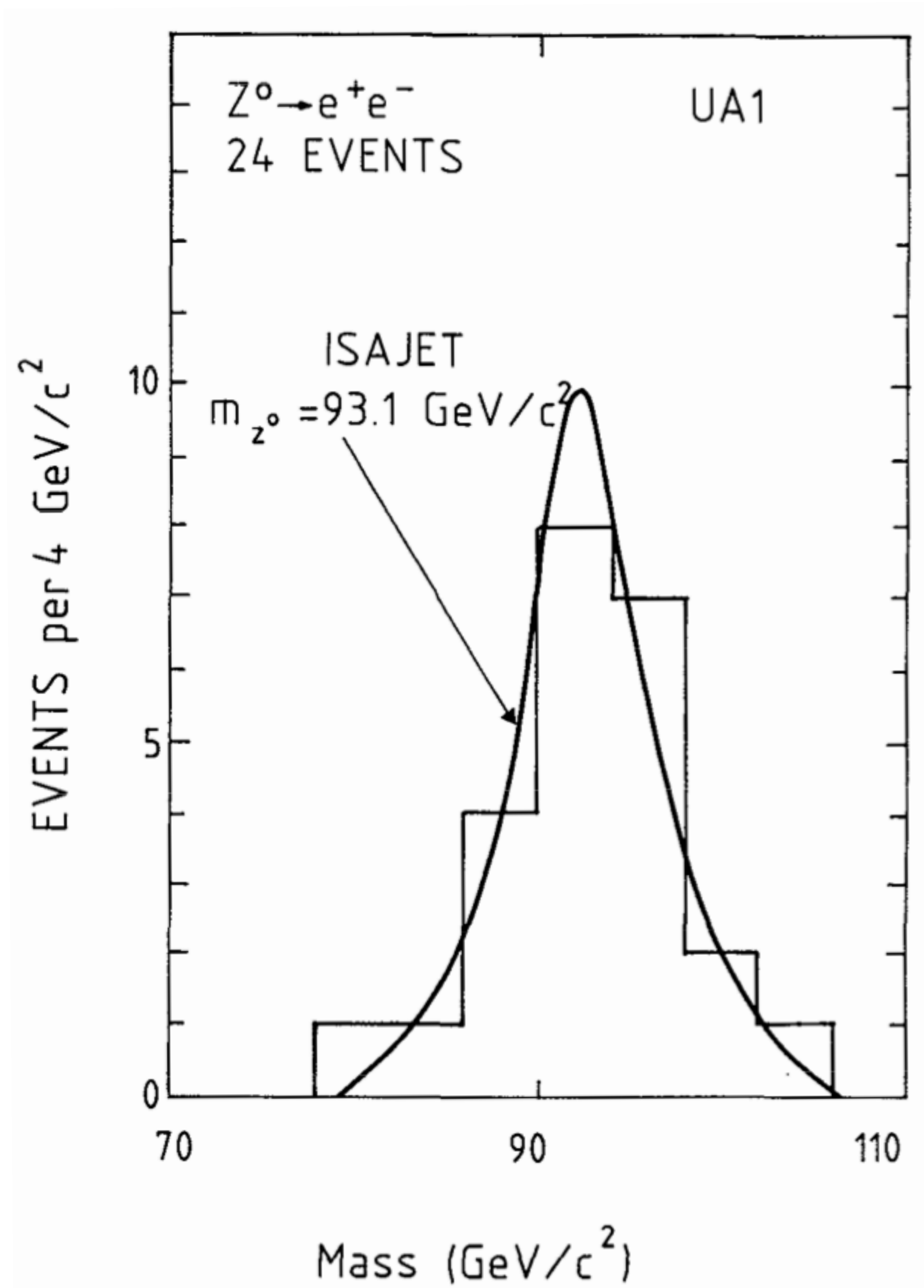
We just discovered a new particle…

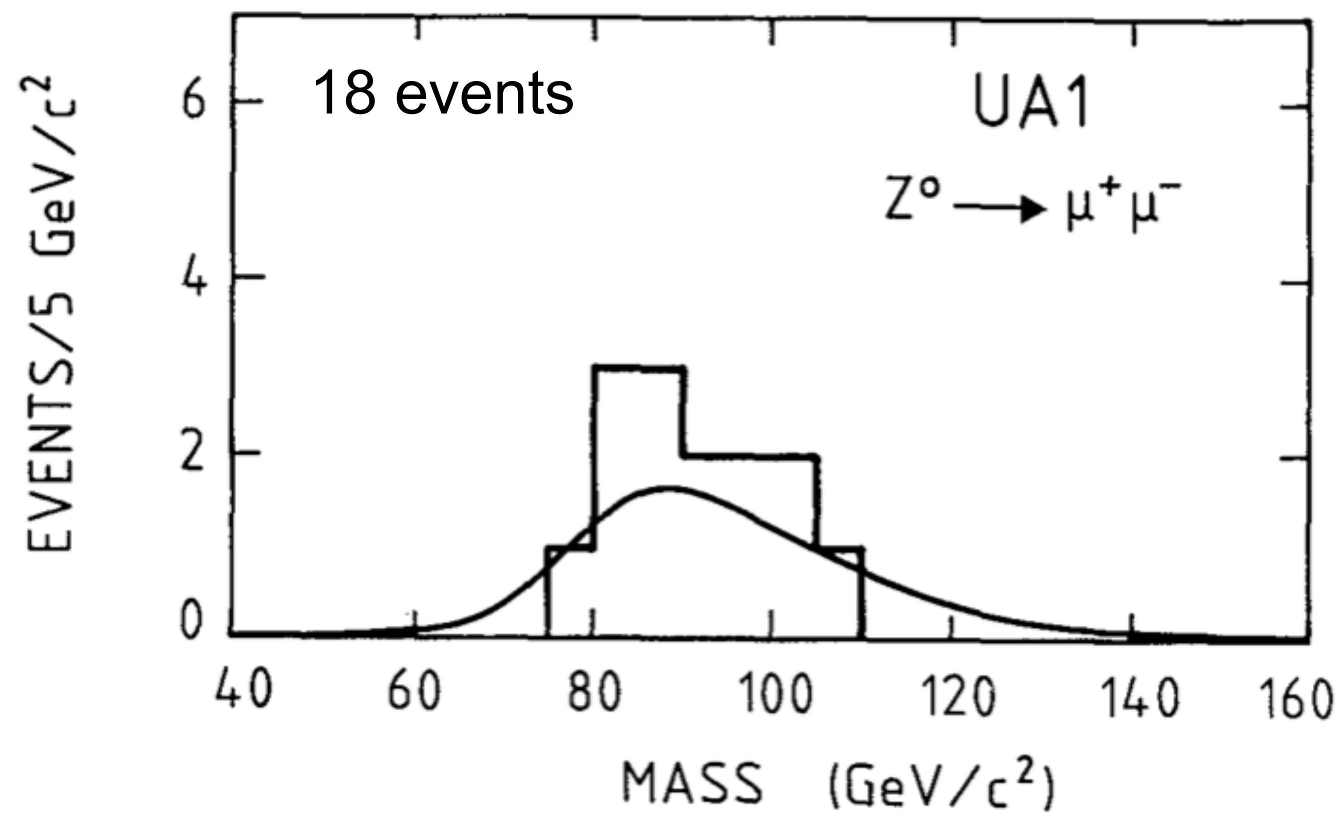




Now what?

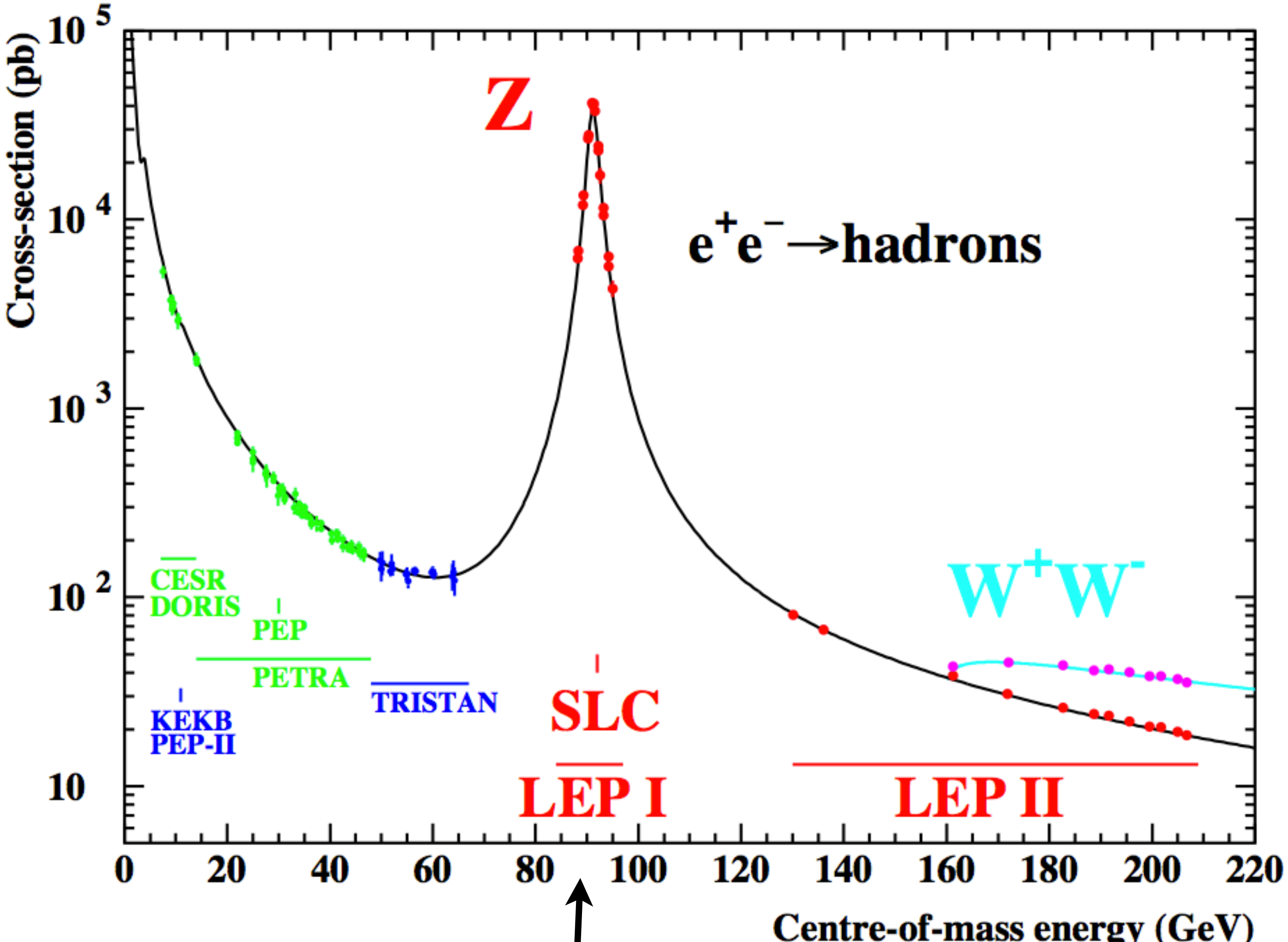
Remember back then?

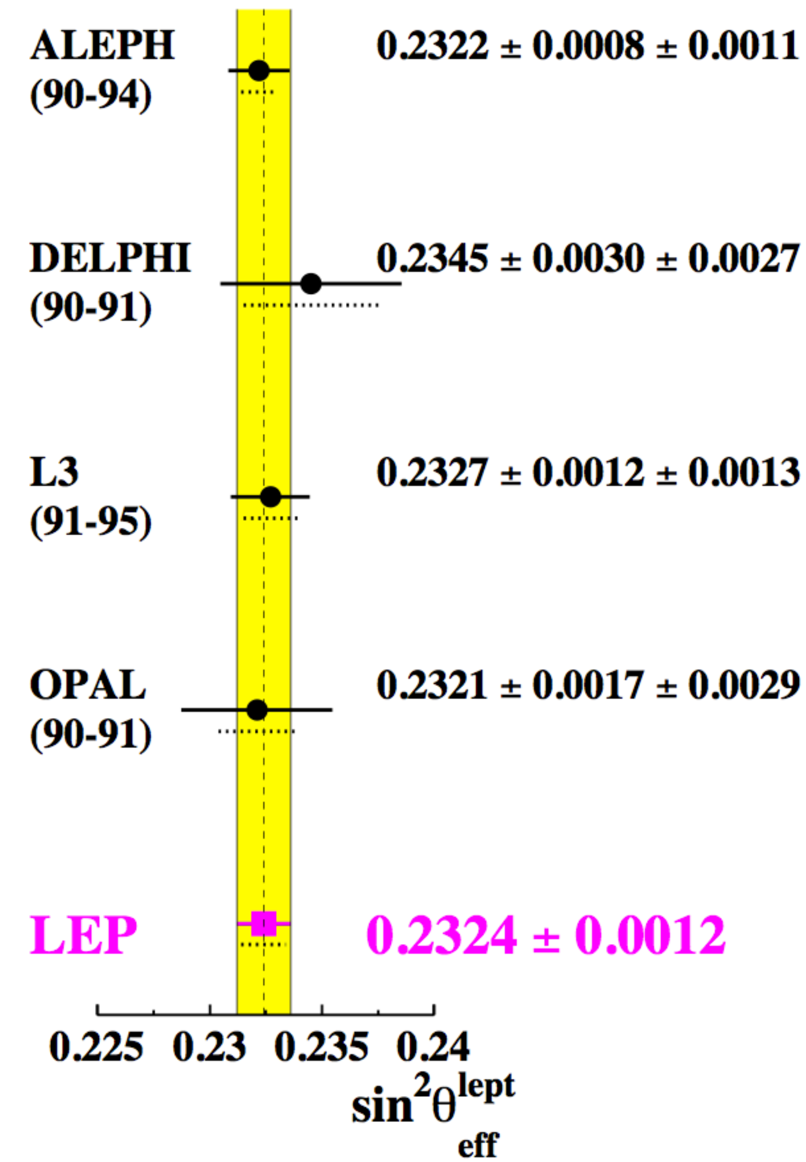




data from 1982-1985

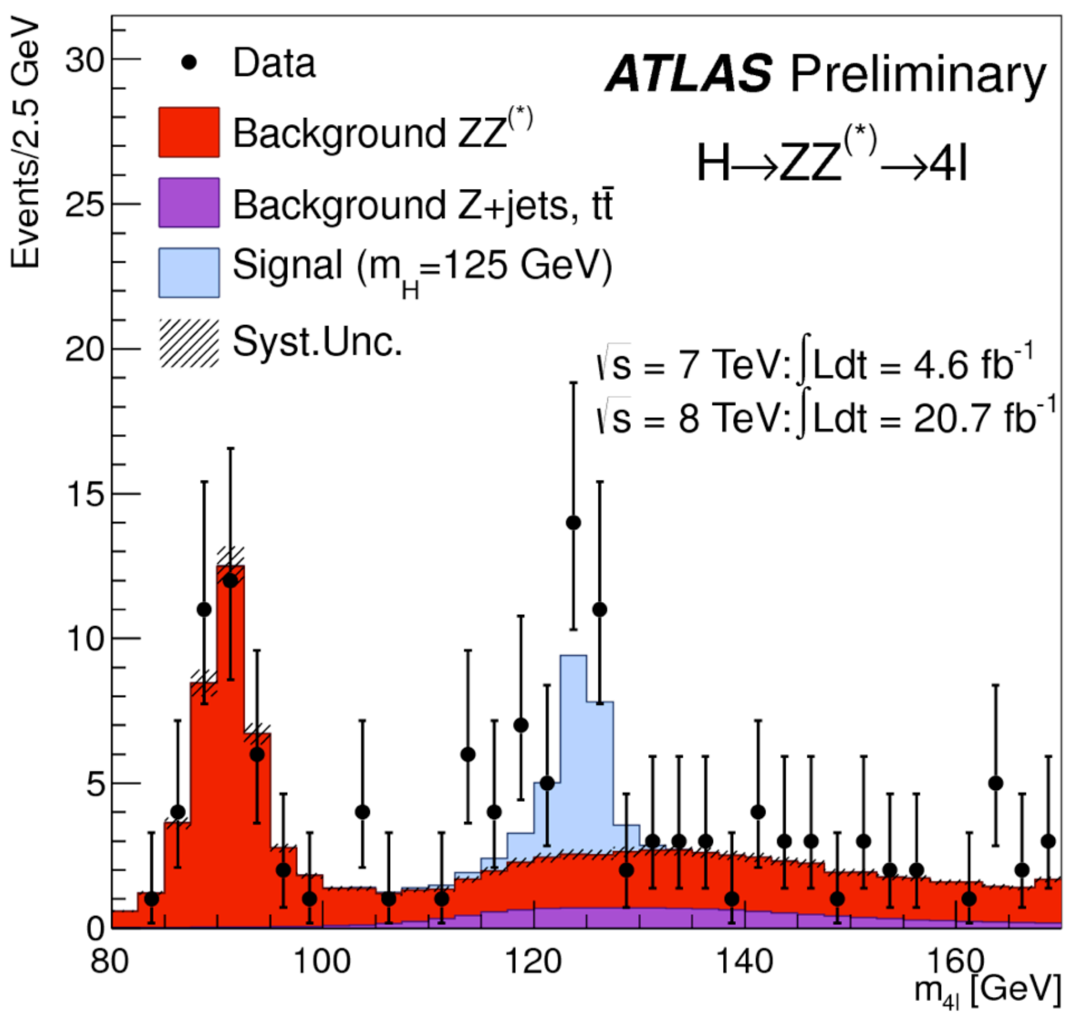
And now…

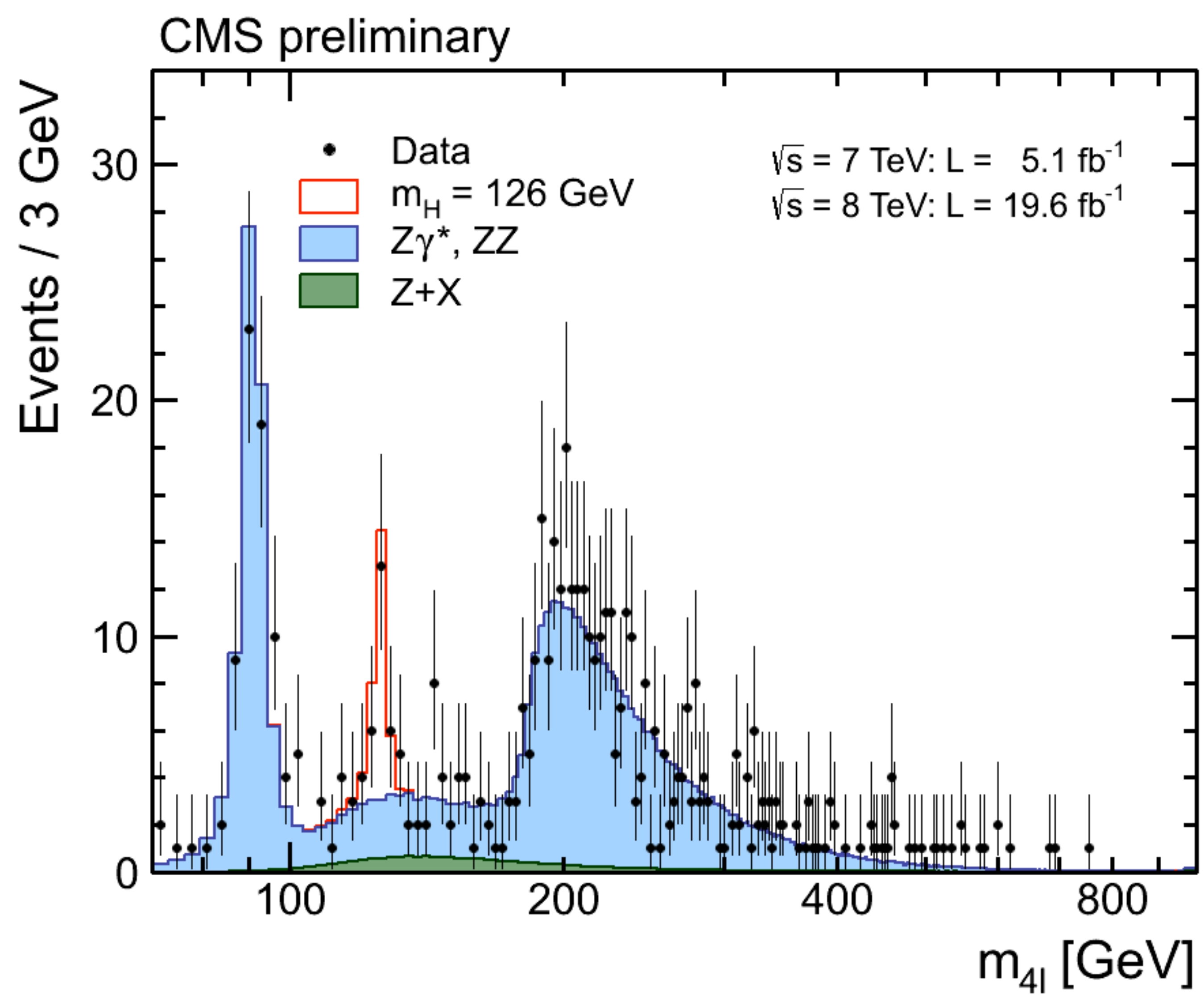




~2×10^7 events

Well, now…





w/ Higgs, we're just at the beginning…

What next?

- more data will better determine couplings to Standard Model states

  clearly, very important to know this…

- *But*: a proper PDG entry should look like this:

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hadrons		(69.91 ±0.06) %		–
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$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ±0.4) %		–
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from: PDG

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from: PDG

rare SM decays
& *non-standard decays*…
limits… but could have discovered something amazing!

Must look for non-standard Higgs decays

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e.g. $h \to 4\gamma$

$h \to 4b$

$h \to \gamma + \not{E}_T$

$\cdots$

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$\dots$

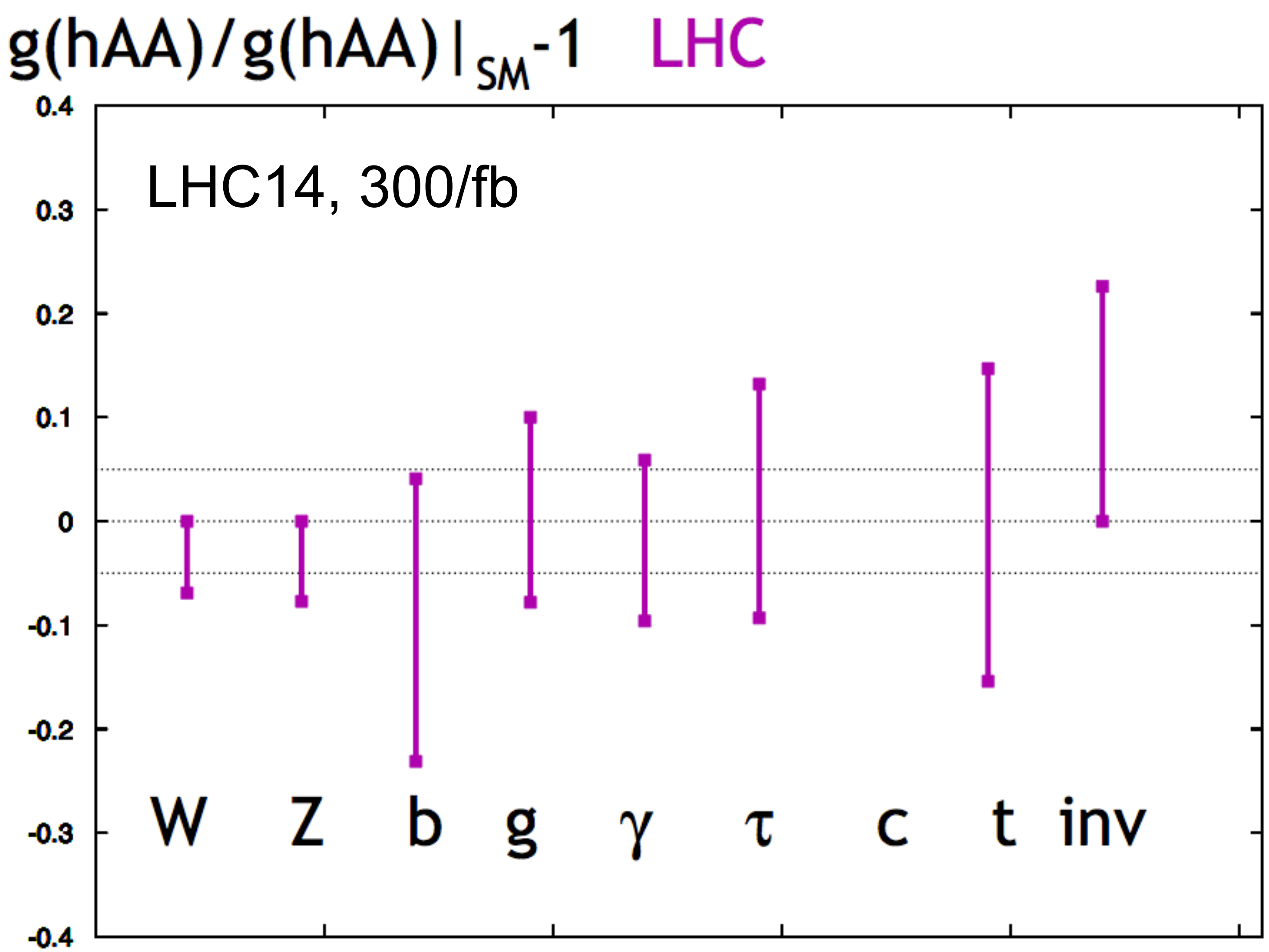
Some searches at LHC

(e.g. CMS: h→4μ, ATLAS: h→4γ, electron-jets, muonic-jets)

But many more analyses need to be done!

There will always be room for exotic decays

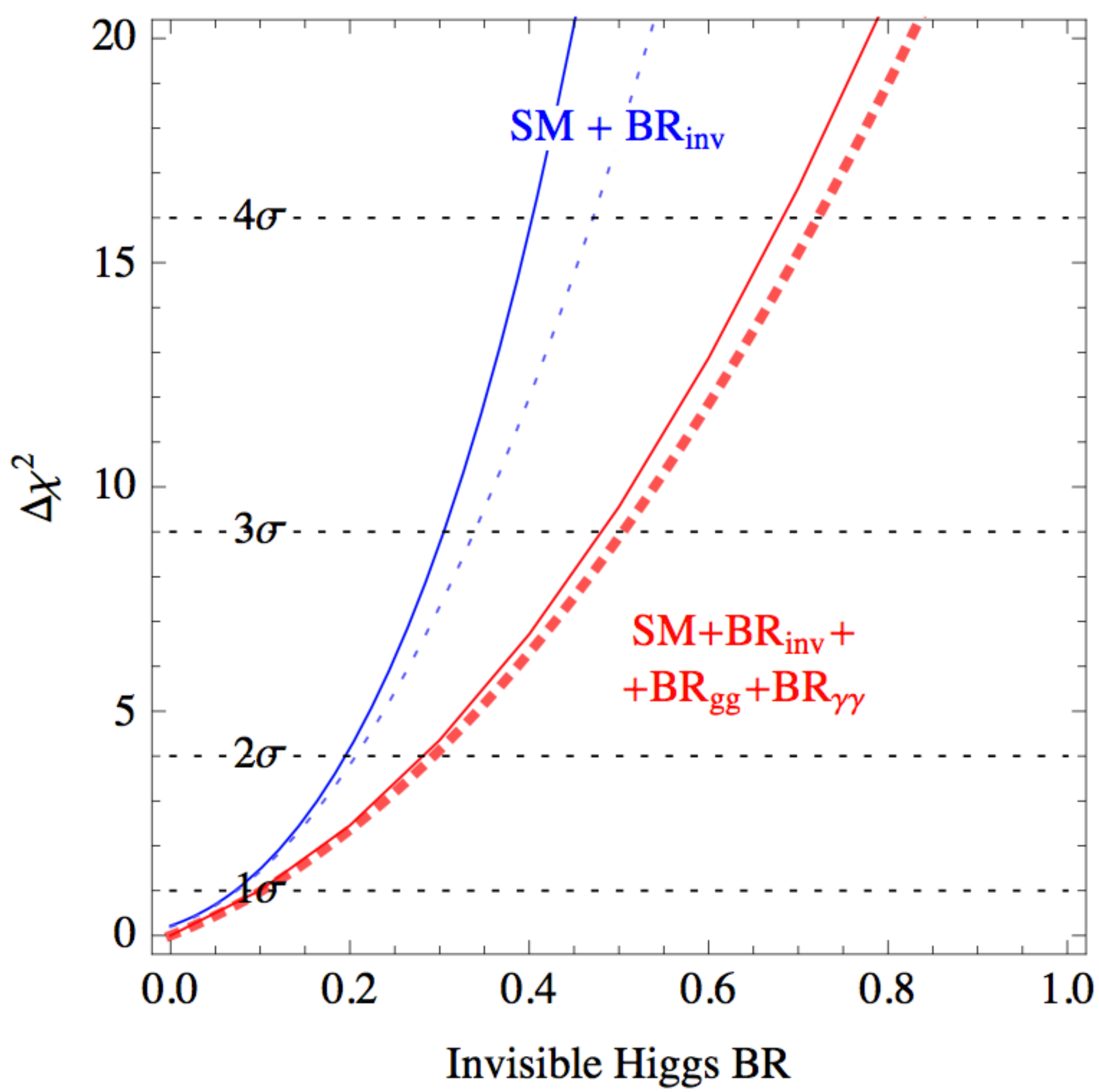
LHC measurements will never determine Higgs couplings to SM particle better than 5-10%



Peskin, 1207.2516

“Invisible” Higgs width

$\mathrm{BR_{inv}} < 0.28$ at 95% C.L. (w/ assumptions)



a lot of room remains!

exotic decays could be much more common than $h\to\gamma\gamma$, $h\to ZZ^*$!

Giardinoa, Kannike, Masina, Raidal, Strumia, 1303.3570

see e.g. also Belanger, Dumont, Ellwanger, Gunion, Kraml; Espinosa, Muhlleitner, Grojean, Trott

Non-standard ("exotic") Higgs decays

- 125 GeV state is thus far only discovery of LHC

  $\Longrightarrow$ must study *everything* about it

- exotic decays could be only window to new physics

- could easily be missed by *all* other searches

- must look for them explicitly w/ dedicated analyses

Immediate Questions

- 125 GeV Higgs looks SM-like… how can it have exotic decays?
- Which exotic decays are possible?
- Which analyses should be done first?
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  Need benchmarks for LHC8 (& LHC14)

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- self-formed group of theorists
- survey, systematize, prioritize non-standard decays
- develop search strategies, assess discovery potential, provide viable benchmark models/points
- inform LHC14 trigger selection
- assemble comprehensive summary document to inform experimental analyses

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modeled after "*Simplified Models for LHC New Physics Searches*" but now focus on Higgs searches

see 1105.2838 (Editors: RE, P. Schuster, M. Lisanti, T. Tait, N. Toro, J. Wacker)

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Note: Matt Strassler has for some time emphasized the importance of this… especially a year ago for LHC8 trigger selection (we're coordinating w/ him)

Exotic Higgs Decays are nothing new!

- Huge and *old* literature!

(e.g. recall the "Hiding Higgs at LEP" days… but even well before then)

e.g. "Invisible decays of Higgs boson", Shrock & Suzuki 1982

- part of our goal is to survey existing literature

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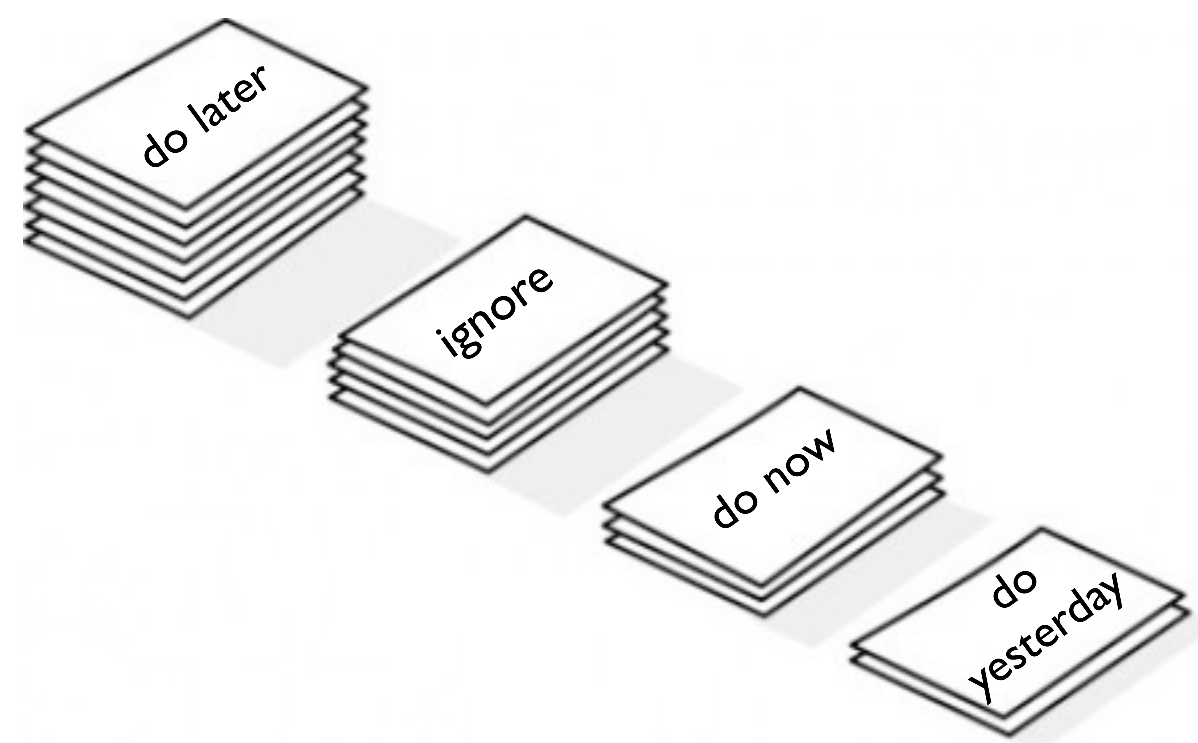

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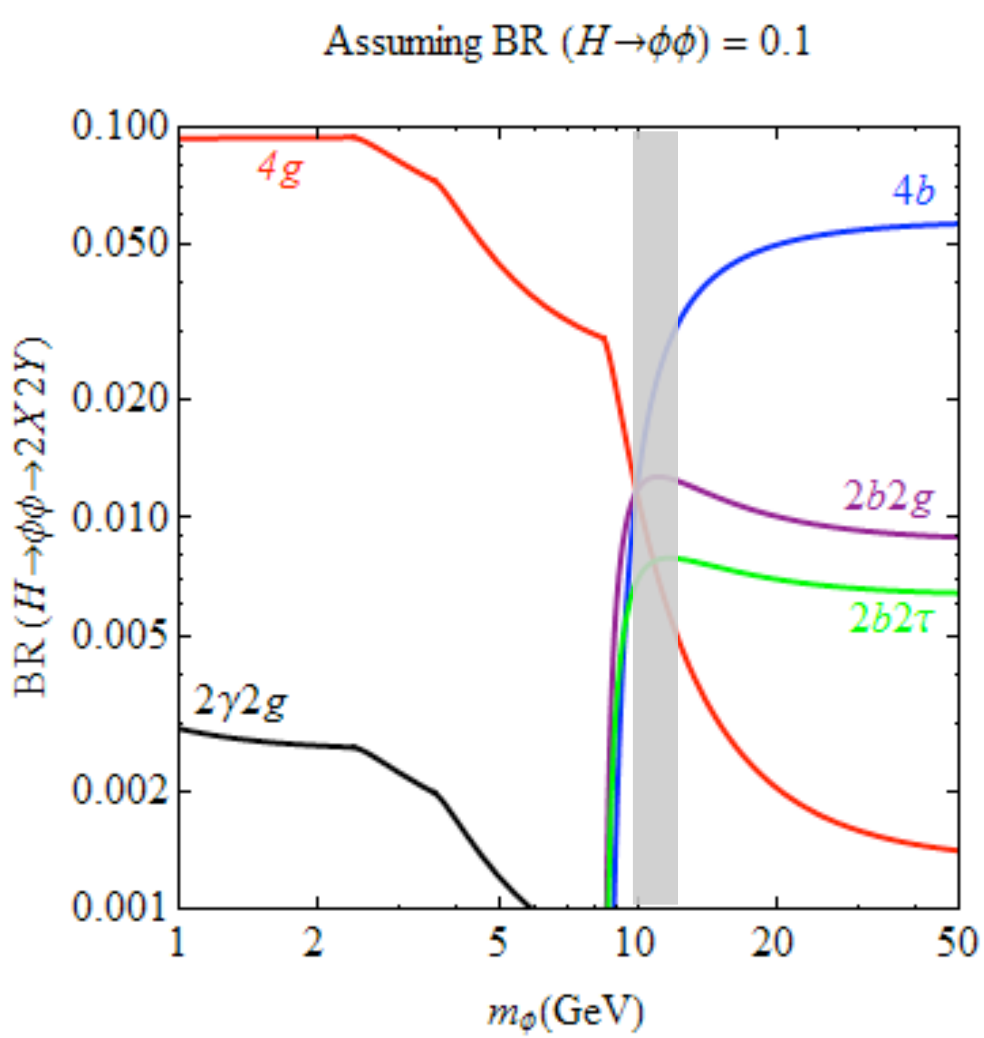
But important to reassess
models after discovery!

Some Comments on Models

Many models!

- Simple example: SM Higgs doublet + (real) singlet ϕ

Prerit Jaiswal, Ze'ev Surujuon



$$h \to \phi\phi \to x\,x\,y\,y$$

x, y = SM particles

plot from
Ze'ev Surujon

for decays in "bottomonium"
window see Baumgart & Katz

Some Comments on Models

Also, many Higgs models have a "decoupling limit" in which there is one SM-like Higgs

- e.g. Two-Higgs-Doublet-Models (2HDM)

see e.g. recent review by Branco, Ferreira, Lavoura, Rebelo, Sher, Silva

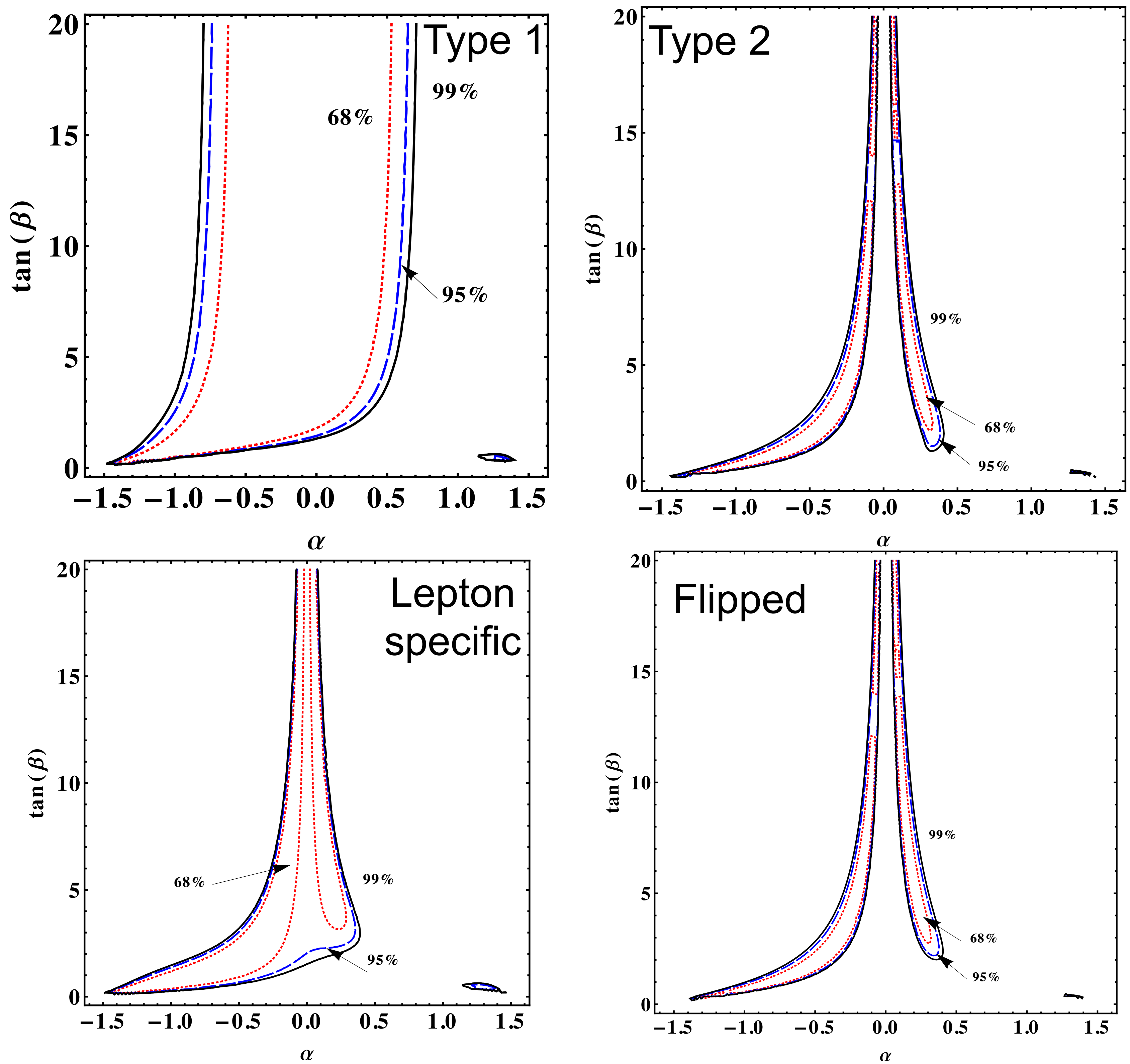
- w/ CP and flavor conservation, 4 popular types:

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

$\longleftarrow$ (MSSM-like)

Some Comments on Models

determine existing constraints on 2HDM, e.g.



e.g. Chien-Yi Chen, Sally Dawson;

+ see talk by N. Craig
+ many other references

This "fixes" some 2HDM parameters

Some Comments on Models

Now add a singlet w/ small mixing w/ Higgs

allows $h \to aa$ &/or $h \to ss$

(pseudo-scalar) (scalar)

Require BR < 10-20%

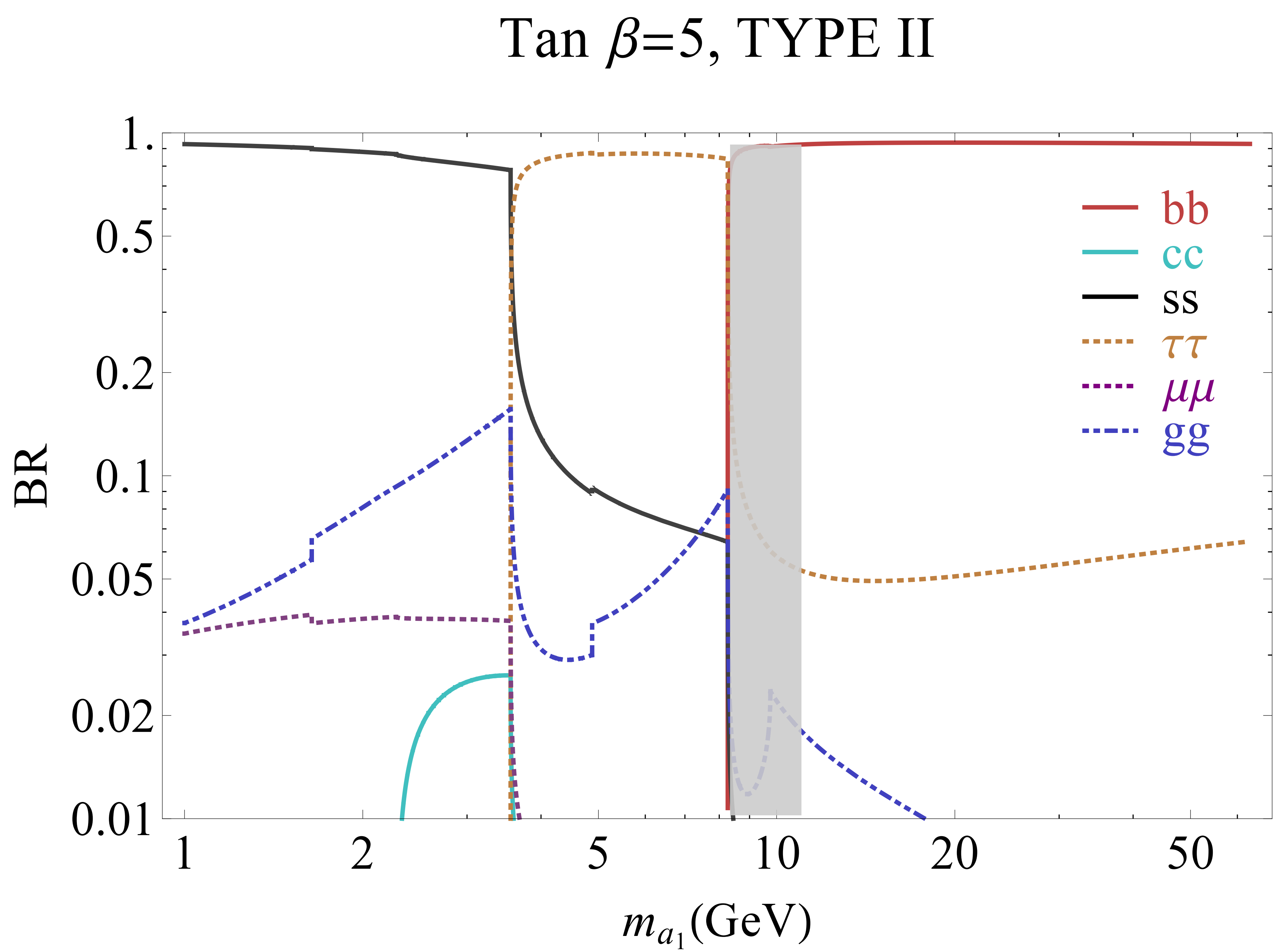
Doesn't qualitatively change the previous constraint plots…

pseudo-scalar (a) and scalar (s) inherit a mixture of Φ_1 and Φ_2 couplings to fermions

Some Comments on Models

e.g. decays of pseudo-scalar

plots from Yiming Zhong



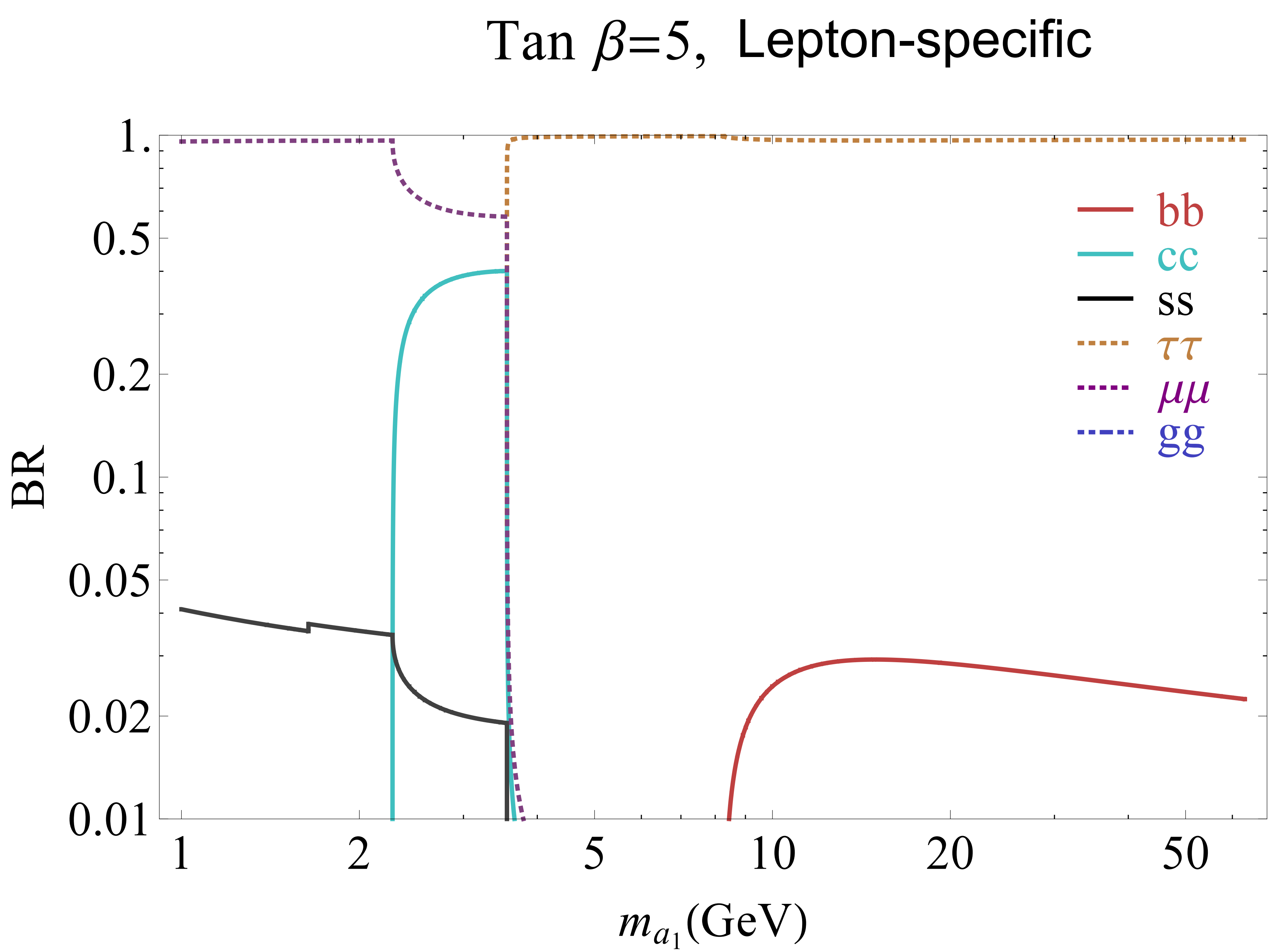
like NMSSM

see talk by Zhen Liu

Some Comments on Models

e.g. decays of pseudo-scalar

plots from
Yiming Zhong



τ's can dominate even above $2m_b$

Many possibilities

Many models consistent w/ Higgs measurements & BSM searches

Many other options exist, e.g.

$$\left.\begin{array}{l} h \to 4x \\ h \to 2x2y \end{array}\right\} x, y = e, \mu, \tau, \gamma, b, j, \not{E}_T, \ldots$$

$$h \to X + \not{E}_T \qquad X = \gamma, 2\gamma, 2\mu, 2\tau, \ldots$$

$h \to \tilde{\chi}_1 \tilde{\chi}_1 \to 6 \text{ SM particles}$ (e.g. R-parity violation)

$h \to 2 \to \text{many}$ (e.g. in Hidden Valleys) Strassler & Zurek

above w/ displaced vertices

need broad array of searches, some easy, some hard

How many exotic decays to expect?

assume BR($h \to aa$) = 10%, LHC8, 20/fb

channel	# events (raw)
ggF	39000
VBF	3150
$W(\ell\nu)+h$	280
$Z(\ell\ell)+h$	55
ttH	260

} Associated Production (AP)

Can always trigger w/ AP… but not many events

Depending on `*a*` decays, ggF/VBF may be better

A few examples (briefly!)

work in progress

(not a prioritized list!)

Example: h → 2a → 4b

David Curtin
RE
Prerit Jaiswal
Ze'ev Surujon
Yiming Zhong

- Decay often dominates for m_a > 10 GeV
- Trigger: AP
- studies in literature done for LHC14

e.g. Carena, Han, Huang, Wagner (2007)
Cheung, Song, Yan (2007)
Kaplan, McEvoy (2011)

  - scaling *naively* to BR(h→aa) = 10%, LHC8, 20/fb

    $S/\sqrt{B} \sim 2$ does not seem impossible

- worth a dedicated study
- improvements possible with substructure, color flow etc.?

Example: $h \to 2a \to 4\tau$

Andrey Katz
Brock Tweedie

- Usually dominates for $m_a < 2m_b$, but sometimes also for $m_a > 2m_b$
- Lots of channels & challenges
  - $\tau \to e, \mu$, 1-, or 3-prong (τ's and leptons soft)
  - "ditau-jets": $\Delta R(a \to 2\tau) \sim 4m_a/m_h \sim 0.3$
  - h/a resonance reconstruction extremely difficult
- Triggers: multilepton, non-isolated muons; VBF
- Tentative plan
  - study ggF and VBF with multiple soft leptons, "$\mu+\tau$" jets
  - recast existing multi-lepton/τ searches

2012 raw harvest, assuming 10% BR($h \to aa$)

2012	inclusive	$2 \times \mu(\tau_h/l)$	$4l$	$\geq 3l$	$\geq 3\mu$	$e\mu/\mu\mu + j_{2\tau}$	no muons
ggF	38000	3400	570	3800	500	4750	17860
VBF	3200	290	50	320	42	400	1500
$W(l\nu)h$	300	30	5	30	4	38	140
$Z(\nu\bar{\nu})h$	150	14	2	15	2	19	70
$Z(l^+l^-)h$	55	5	1	6	1	7	26

* e.g., raw 4l rate 10x larger than h_{SM}, but non-resonant & *soft*

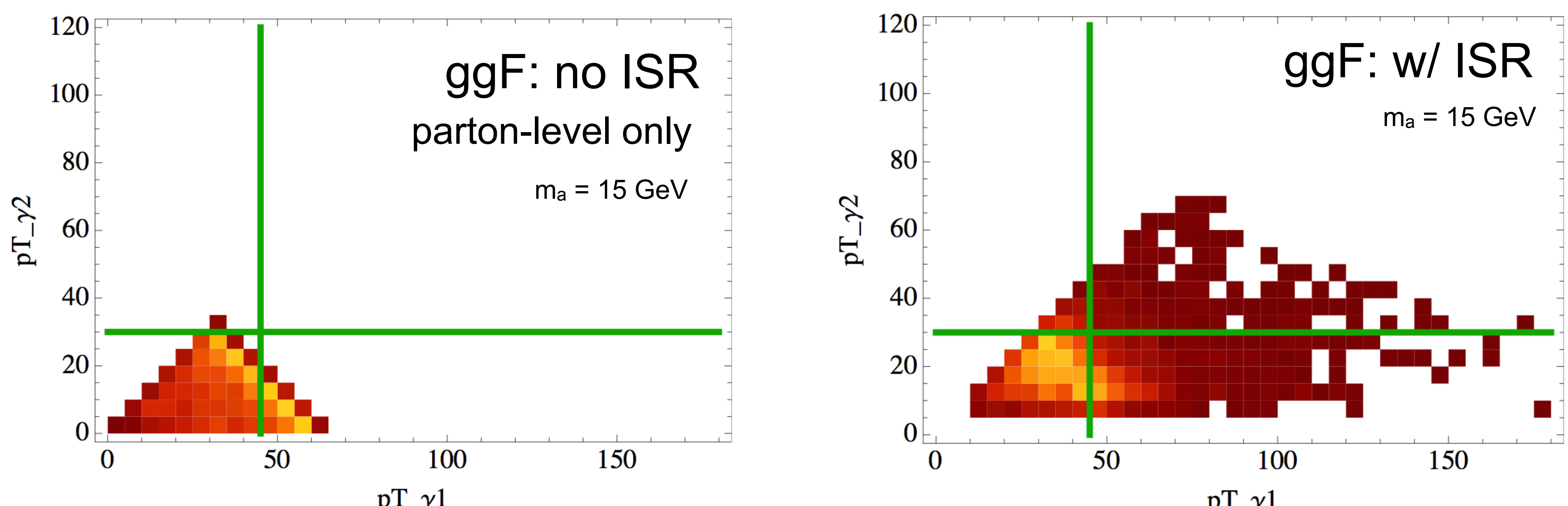
Example: h → 2a → 2j+2γ

David Curtin
RE
David McKeen
Ze'ev Surujon
Yiming Zhong

- a → gg & a→γγ can be comparable in some models
- can trigger w/ lepton(s) from AP

e.g. Martin

- ggF & VBF worth investigating; di-photon trigger perhaps sufficient for resolved photons (heavier m_a)



Plots from Prerit Jaiswal & David Curtin

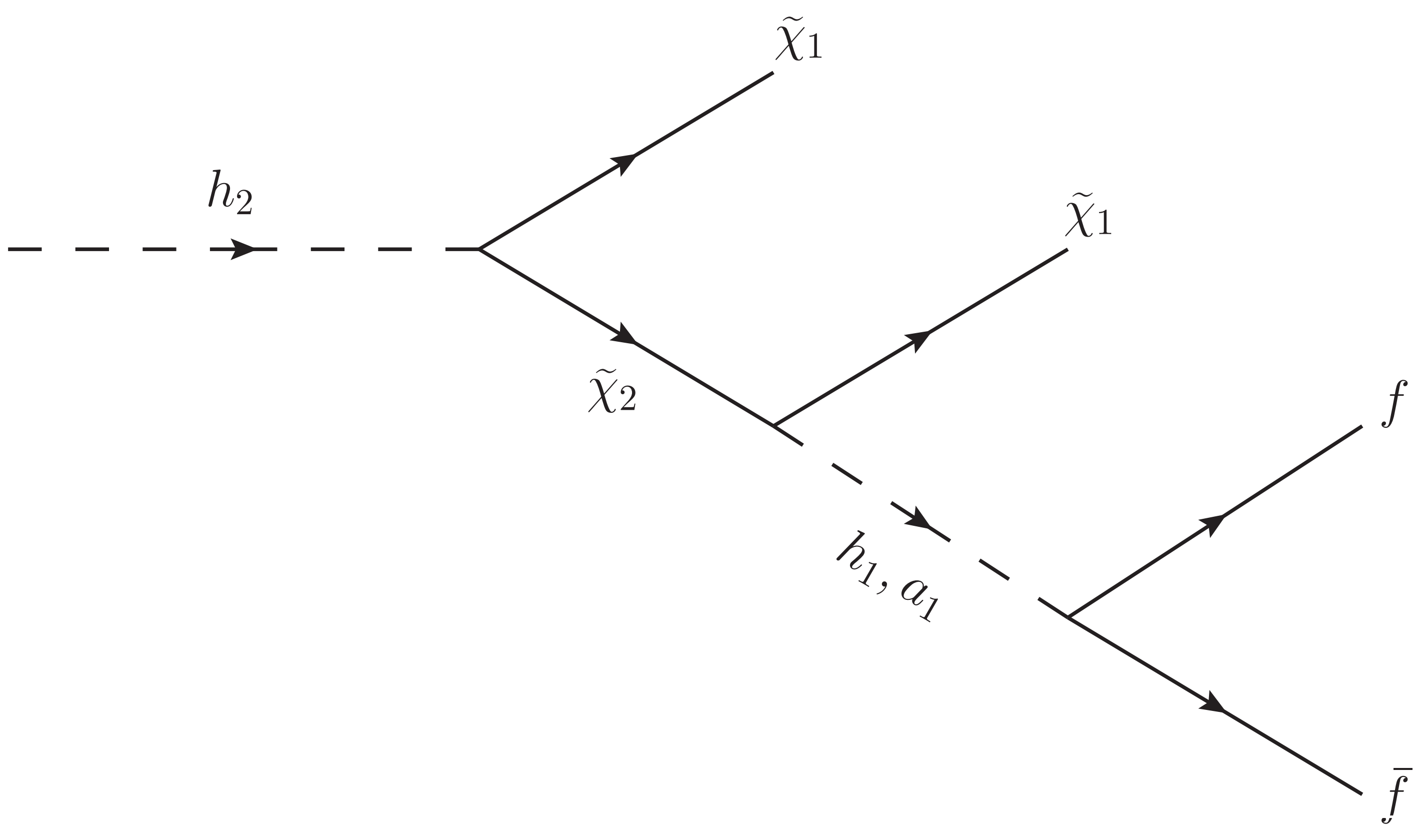
Example: h → Soft Leptons or Jets + MET

Tao Liu

- In PQ limit of MSSM+singlet, typically have 3 light particles: h_1, a_1, χ_1

Draper, TL, Wagner, Wang, Zhang (2011)

- can have:

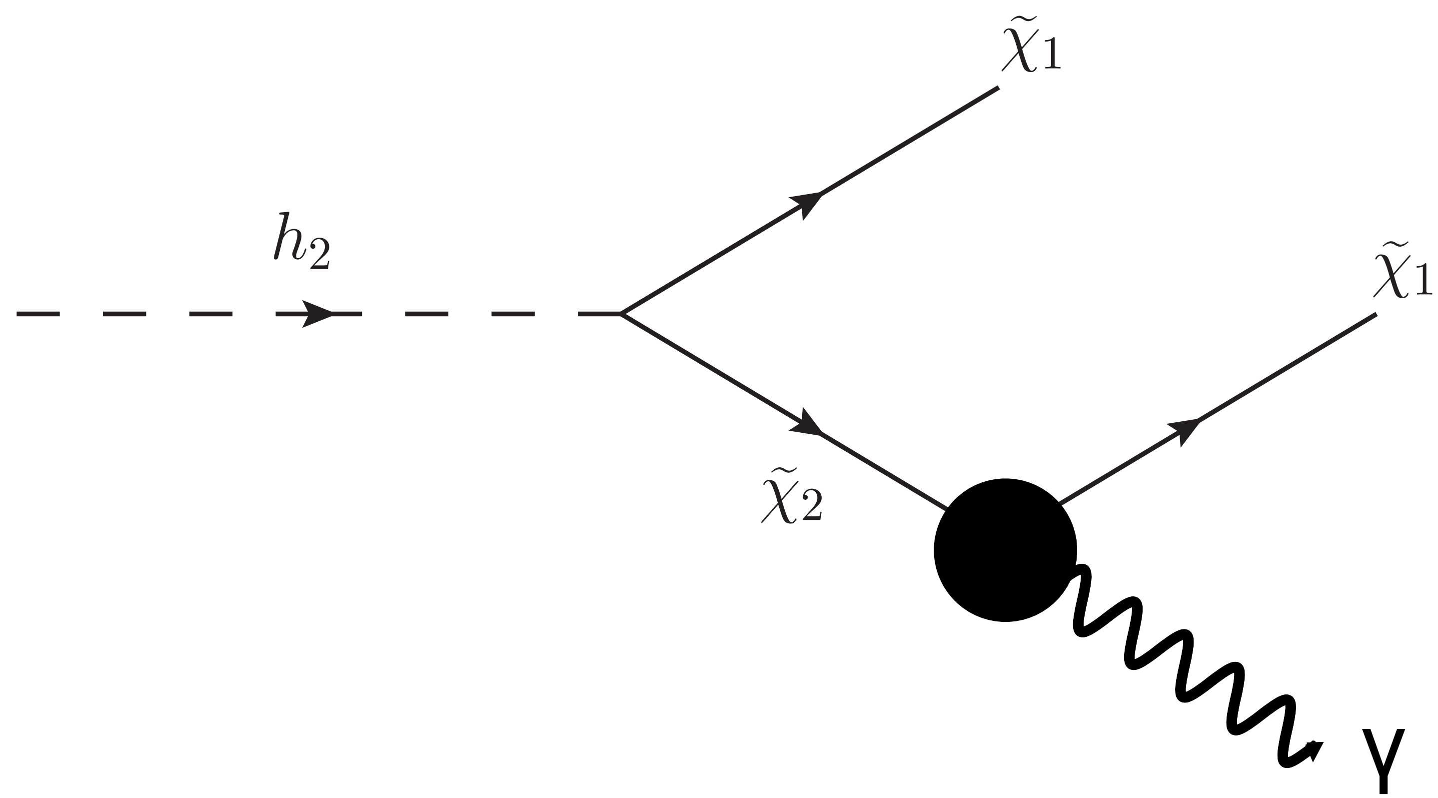


- LHC analyses for h_1 or a_1 → bb, $\tau\tau$, $\mu\mu$ in progress

Example: h → γ + MET (or 2γ + MET)

Stefania Gori
Tao Liu
Jessie Shelton

- e.g. in same PQ limit, but w/ $m_{\chi 1} \sim m_{\chi 2}$, could also have



- Or, e.g. $h \to \tilde{G}\tilde{B}, \; \tilde{B} \to \gamma\tilde{G}$

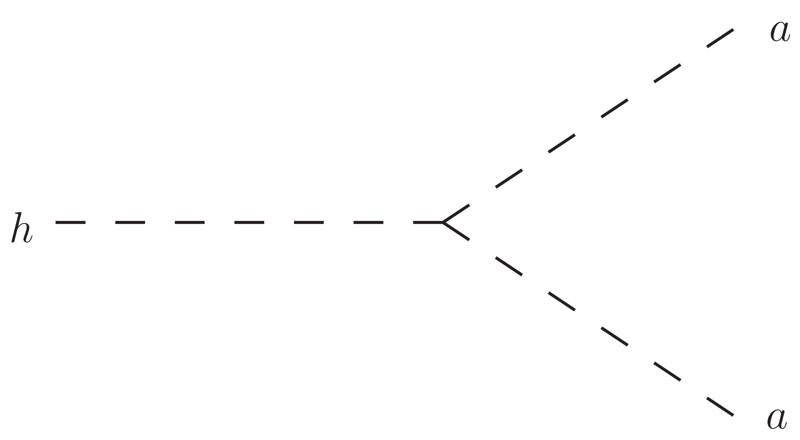
Djouadi, Drees; Petersson, Romagnoni, Torre

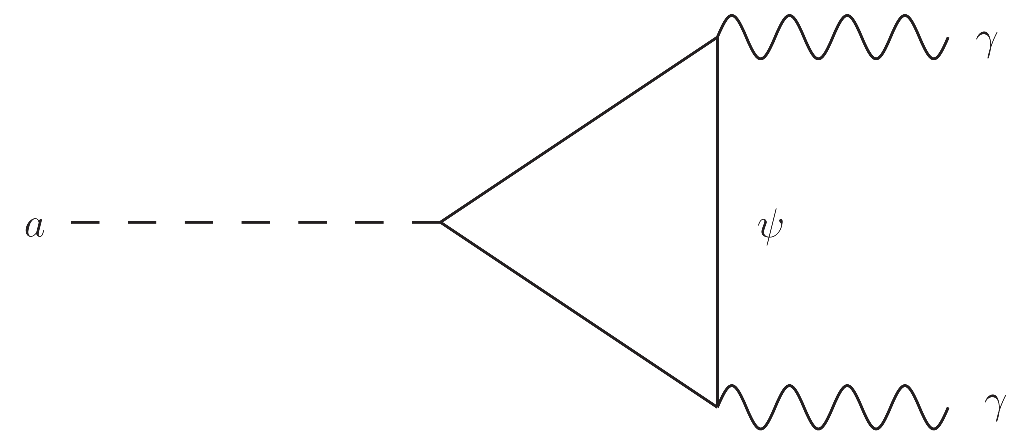
For γ + MET:

- Estimate 5.5σ for BR = 10% in 5 fb^{-1} for ggF and 3.5σ in VBF

Example: $h \to 4\gamma$

David McKeen





- BR($a \to 2\gamma$) large in some models; displaced decays for $m_a \ll m_\psi$
- BR($h \to 4\gamma$)~10^{-5} for $m_h \sim 125\ \mathrm{GeV},\ m_a > 10\ \mathrm{GeV}$ (LHC14, 300 fb^{-1})

Chang, Fox, Weiner

- light m_a: collimated γ's, contribute to $h \to \gamma\gamma$ if $m_a \ll m_h$
  - ATLAS LHC7 4.9 fb^{-1}: BR($h \to 4\gamma$)<1% ($m_a \sim 100 - 400\ \mathrm{MeV}$)

Dobrescu, Landsberg, Matchev (Tevatron)
Draper & McKeen (LHC)
ATLAS-CONF-2012-079

- Relax isolation cuts & allow displaced vertices

Summary

Higgs may be our (only) window to new physics:
must look *explicitly* for non-standard decays of Higgs

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Higgs may be our (only) window to new physics:
must look *explicitly* for non-standard decays of Higgs

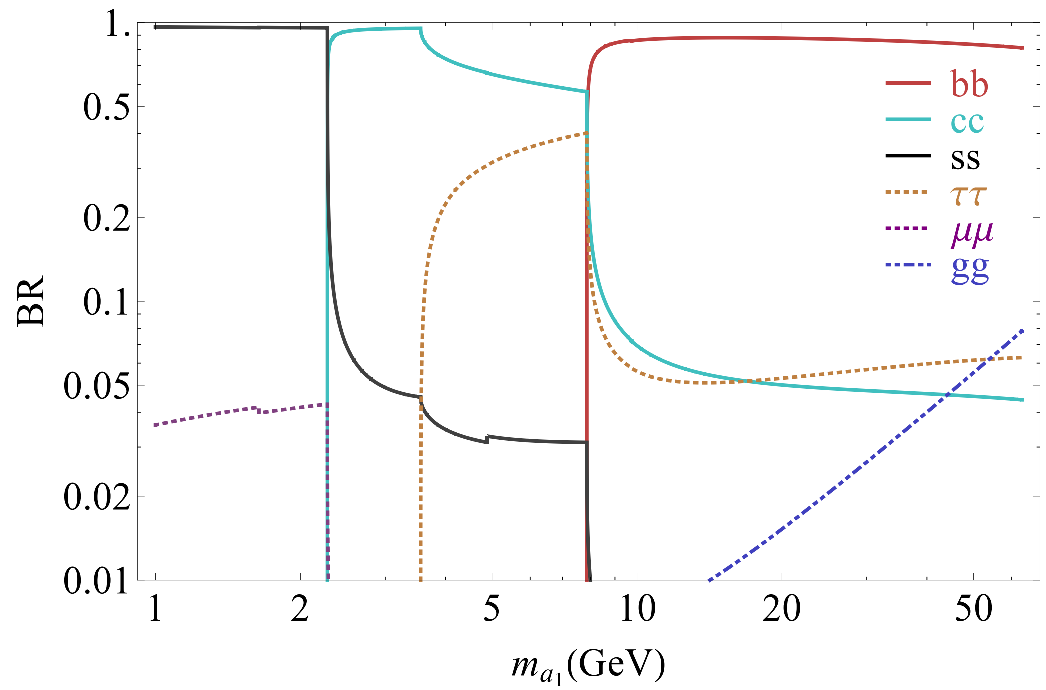
- our group will survey, systematize, prioritize possibilities
- develop search strategies, assess discovery potential, provide viable benchmark models/points for LHC8
- inform LHC14 trigger selection
- comprehensive summary document in preparation to inform experimental analyses

Backup

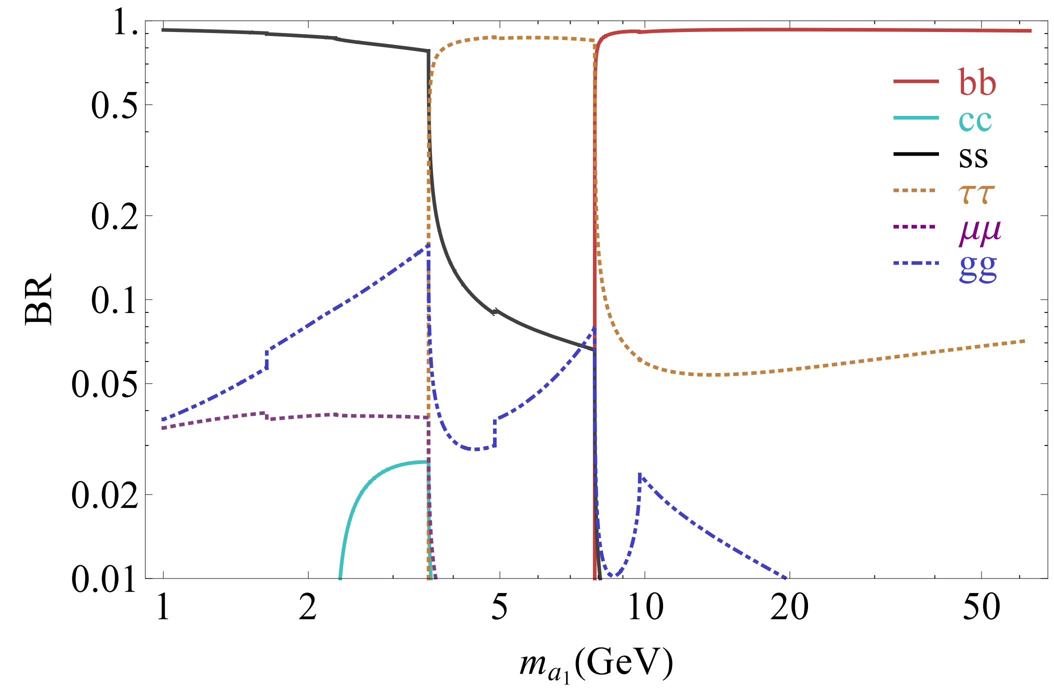
Decays of pseudo-scalar in 2HDM w/ singlet

plots from Yiming Zhong

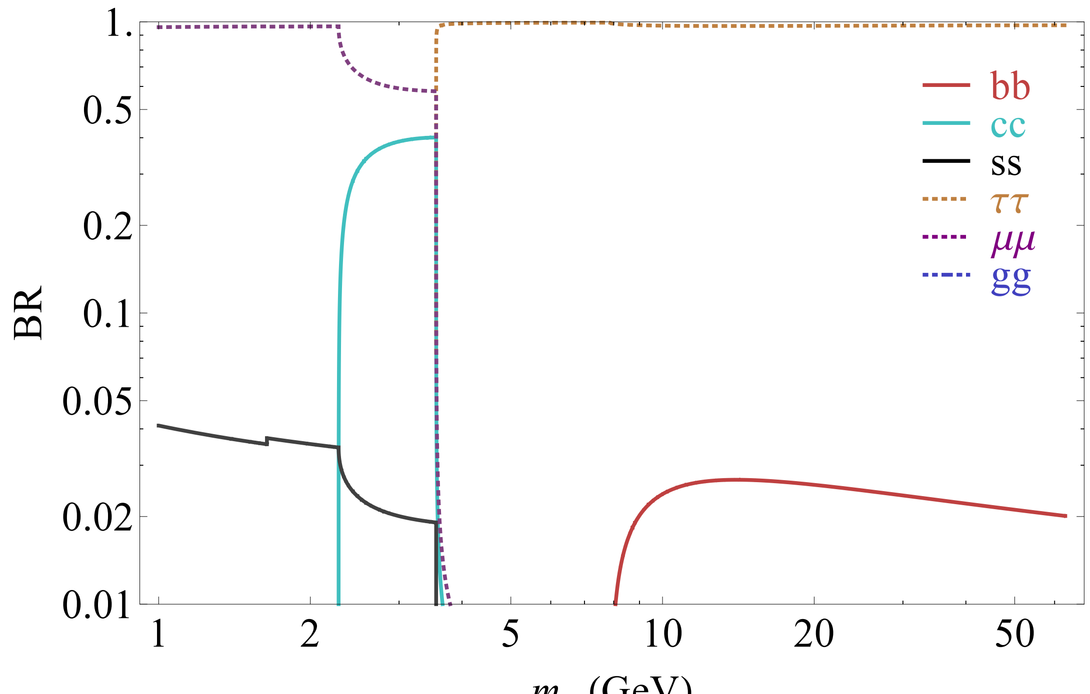
Tan β=5, TYPE I



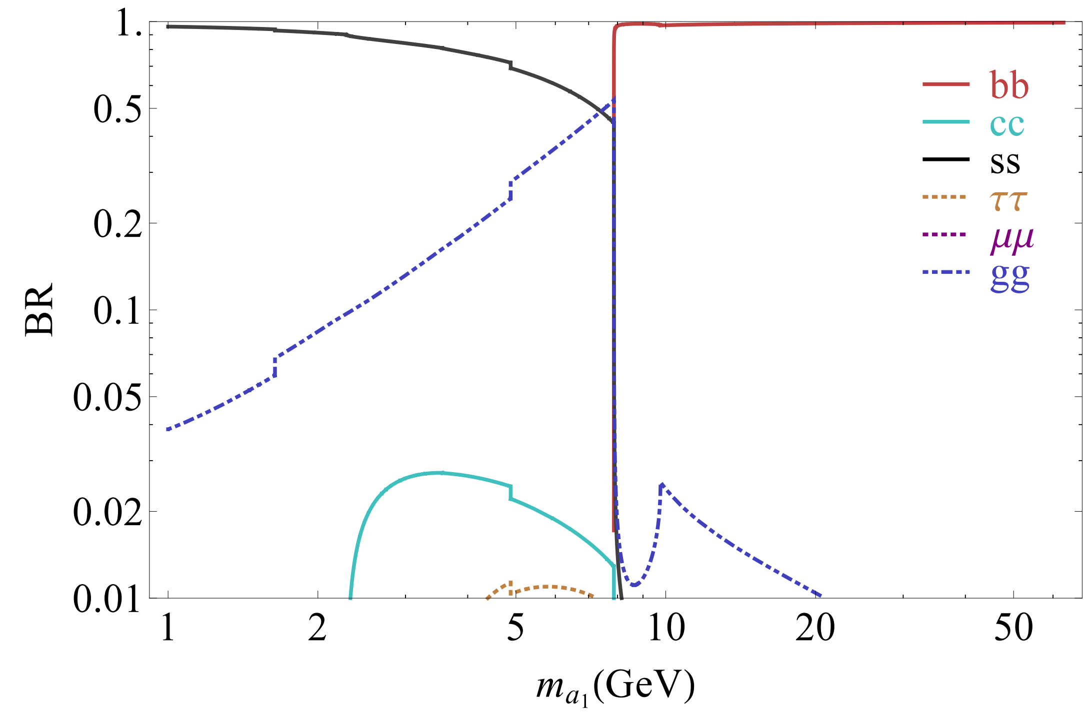
Tan β=5, TYPE II



Tan β=5, Lepton-specific

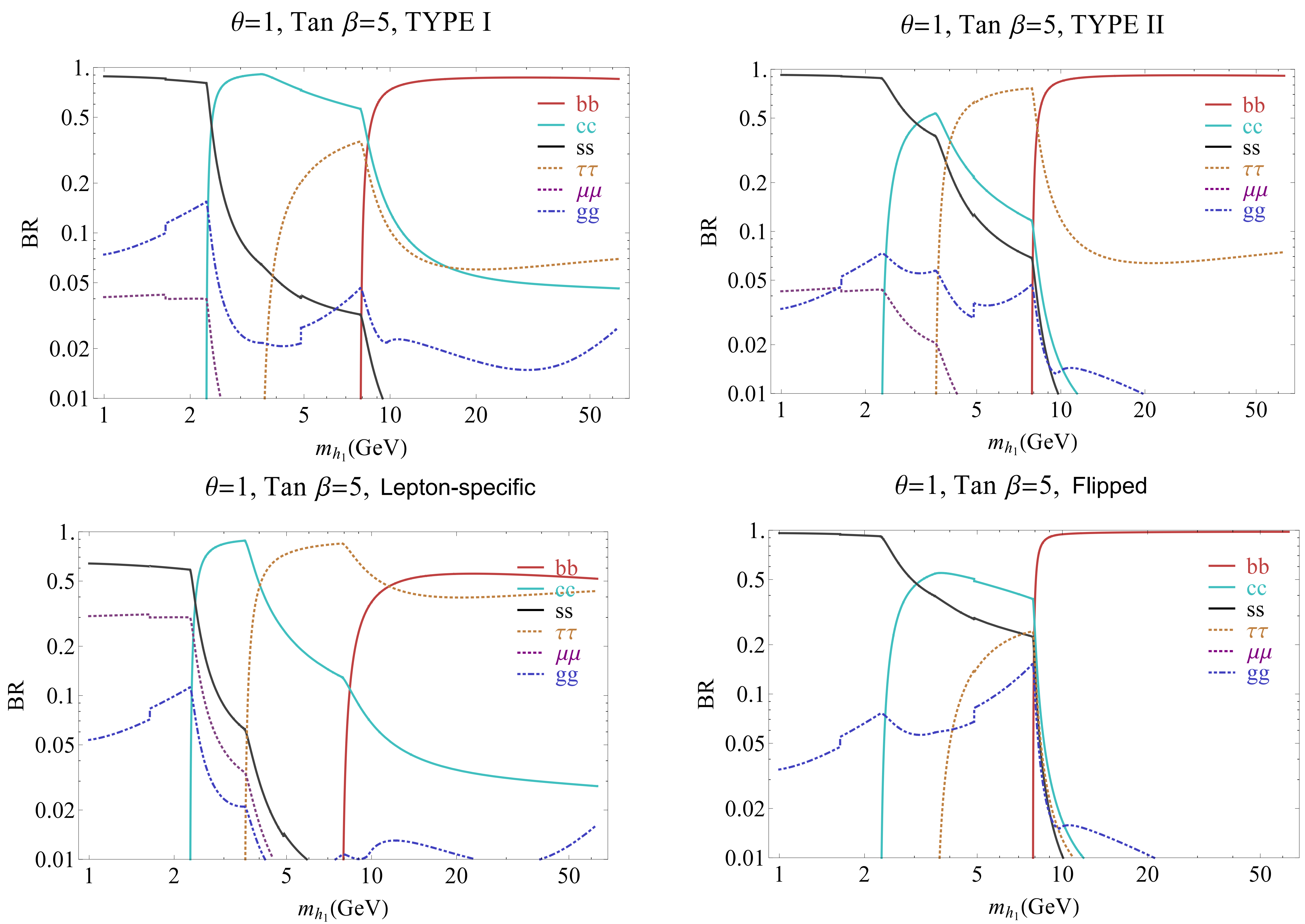


Tan β=5, Flipped



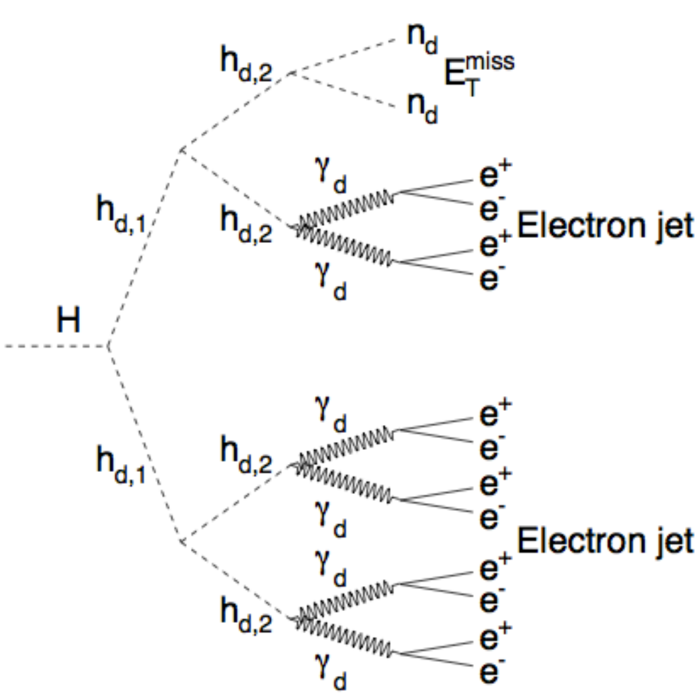
Decays of scalar in 2HDM w/ singlet

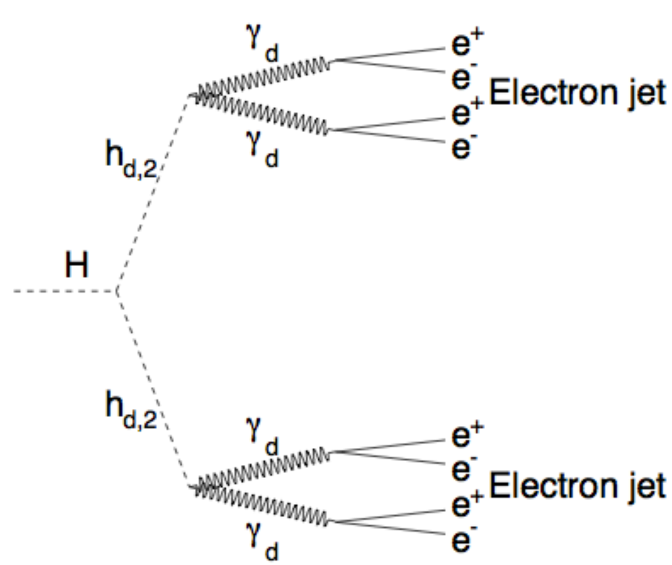
plots from
Yiming Zhong



Some LHC searches

- CMS [arXiv:1210.7619]: Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states
- ATLAS [arXiv:1302.4403]: Search for WH production with a light Higgs boson decaying to prompt electron-jets in proton-proton collisions at $\sqrt{(s)}$=7 TeV with the ATLAS detector
- ATLAS [arXiv:1210.0435]: Search for displaced muonic lepton jets from light Higgs boson decay in proton-proton collisions at $\sqrt{\{s\}}$=7 TeV with the ATLAS detector
- ATLAS-CONF-2012-079: Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb−1of 7 TeV pp collision data taken with ATLAS detector at the LHC





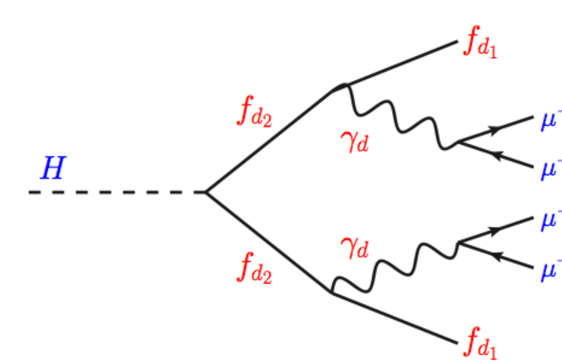


Figure 1: Schematic picture of the Higgs boson decay chain, H→2($f_{d2} \rightarrow f_{d1}\gamma_d$). The Higgs boson decays to two hidden fermions (f_{d2}). Each hidden fermion decays to a γ_d and to a stable hidden fermion (f_{d1}), resulting in two muon jets from the γ_d decays in the final state.